

TEST BOARD DE-EMBEDDING METHOD TO IMPROVE RF MEASUREMENTS
ACCURACY ON AN AUTOMATIC TESTING EQUIPMENT FOR IC WAFERS

BACKGROUND OF THE INVENTION

Field of the Invention

5 The present invention relates to a test board de-embedding method to improve RF measurements accuracy on an automatic testing equipment for IC wafers.

 More specifically, the invention relates to a test board de-embedding method to improve RF measurements accuracy on an automatic testing equipment for IC wafers, wherein each wafer includes a device under test located on a wafer die plane and
10 being contacted by probecard needles of a probecard that is coupled to a configuration board through a probe interface board.

Description of the Related Art

 As is well known in this specific technical field, there is a great need to calibrate an automatic test equipment (ATE) and to de-embed the test boards at wafer level.
15 This is particularly difficult because the connection between a RF tester instrumentation of the ATE and the integrated device or circuit to be tested on the wafer is not direct.

 For this reason, the RF measurements are often inaccurate because of the values measured on the bench and the related correlation operations with the bench.

 We will also refer hereinafter to the ATE with the brief appellation of
20 "tester".

 The IC wafer, in fact, is contacted by a board known as "probecard" that contains the needles ring for the contact. The probecard is coupled to a configuration board through a probe interface board (PIB).

 The probecard and the PIB depend on the particular device under test (DUT)
25 while the configuration board doesn't depend on the DUT. Normally, the configuration

board is a front end board that allows to setup the ATE in a plurality of configurations or options.

As clearly shown in Figure 2, the tester includes two microwave ports that are connected to the PIB (Probe In Board) through the configuration board that depends on the particular configuration of the tester.

When an automatic calibration routine is invoked, or a user command "calibrate-uwport" is selected, the RF calibration is performed and the calibration plane is set at an internal plane, inside the ATE.

This means that, in order to have calibrated measurements at the wafer die level, there is a need to extend the calibration plane from the "Internal Plane" to the "Wafer Die Plane". Those planes are clearly shown in Figure 2.

However, up to now no wafer calibration standards have been provided to allow this kind of calibration. In other words, according to the prior art it is not possible to transfer the calibration plane up to the wafer level.

Typically, at present, two known procedures are used, depending on the environment in which the device under test (DUT) has to be tested.

A first procedure is used in the production environment and implements the following steps:

1. Calibration up to the Configuration-Board Plane;
2. Scalar correction factors evaluation from bench correlation.

A second procedure is used in the development environment and implements the following steps:

1. Calibration up to the Configuration-Board Plane;
2. De-embedding of PIB using coaxial OSP Calibration Standards;
3. Scalar correction factors evaluation from bench correlation.

Both these procedures are affected of the following problems:

- the measurement accuracy on ATE is strongly dependent on the bench accuracy;

- all the errors, made during the correlation operation, are transferred to the correction factors evaluation;
- correction factors depend on the status of the test boards and then they have to be periodically upgraded;
- 5 - correction factors depend on the status of the tester and then they have to be upgraded each time maintenance actions have made on the tester.

Moreover, the bench correlation action is characterized, normally, by a too big cycle-time:

$$T \geq 20 \text{ days}$$

10 The aim of the present invention is to provide a technique for calibrating an Automatic Test Equipment (ATE) and for de-embedding the test-boards at wafer level.

A further aim of the present invention is to provide a simple way to design and perform a calibration standards on wafer, in particular for a device under test (DUT).

BRIEF SUMMARY OF THE INVENTION

15 According to one embodiment of the invention a tester calibration and de-embedding method is provided to improve RF measurements accuracy on an automatic testing equipment for IC wafers by implementing a test board de-embedding phase, wherein each wafer includes a device under test located on a wafer die plane and being contacted by probecard needles of a probecard that is coupled to a configuration board
20 through a probe interface board, the method including the following phases:

- performing an automatic calibration phase of said testing equipment up to an internal plane located inside said automatic testing equipment;
- performing a calibration plane transfer up to a plane of said configuration board using a predetermined number of calibration
25 standard loads realized on said wafer;
- performing a test boards de-embedding phase up to the wafer die plane.

This approach is suitable either in development and production environment and, as will be explained, it avoids performing any correlation actions.

The features and advantages of a method and tester according to the invention will be apparent from the following description of an embodiment thereof, given by way of non-limiting example with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

5 Figure 1 shows a block diagram of a conventional test board instrumentation for an Automatic Test Equipment (ATE);

 Figure 2 shows a schematic view of the interconnections between a tester instrumentation and a Device Under Test (DUT) according to the prior art;

 Figure 3 shows a schematic view of a passive network including complex S
10 parameters to define a reciprocal transmission line;

 Figure 4 shows a schematic view of the passive and reciprocal network of Figure 3 using simplified three-term parameters;

 Figure 5 is a schematic block diagram of a micro-wave port incorporated into a known tester of a standard calibration system for IC wafer testing;

15 Figure 6 shows the waveform of a reflected microwave as compared to an incident wave;

 Figure 7 is a schematic view of an Integrated Circuit having a pad terminal presenting an Open circuit (enlarged view) as a calibration standard according to the present invention;

20 Figure 8 is a schematic view of an Integrated Circuit having a pad terminal presenting a Short circuit (enlarged view) as a calibration standard according to the present invention;

 Figure 8A is a schematic view of an Integrated Circuit having at least a pad terminal connected to a Load (enlarged views) as a calibration standard according to the
25 present invention, in a splitted and unsplit configuration respectively;

 Figures from 10 to 16 are a series of Smith Chart schematic representations relating to a probe station with calibrated "Signal-Ground Cascade Probes" working in the frequency range from 1.5 to 2.5 GHz;



Figure 17 shows a schematic view of the interconnections between a tester instrumentation and a Device Under Test (DUT) according to the present invention;

Figure 18 shows a diagram reporting the result of a calibration standards set for a resistor load L1;

5 Figure 19 is a Smith Chart schematic representation showing a capacitance measurements comparison relating to the probe station and the ATE after the de-embedding phase of the present invention with the resistor load L1;

Figure 20 reports a diagram showing a corresponding correction factors array for the results of the Figures 18 and 19;

10 Figure 21 shows a diagram reporting the result of a calibration standards set for a resistor load L2;

Figure 22 is a Smith Chart schematic representation showing a capacitance measurements comparison relating to the probe station and the ATE after the de-embedding phase of the present invention with the resistor load L2;

15 Figure 23 reports a diagram showing a corresponding correction factors array for the results of the Figures 21 and 22;

Figure 24 shows a diagram reporting the result of a calibration standards set for a resistor load L3;

20 Figure 25 is a Smith Chart schematic representation showing a capacitance measurements comparison relating to the probe station and the ATE after the de-embedding phase of the present invention with the resistor load L3;

Figure 26 reports a diagram showing a corresponding correction factors array for the results of the Figures 24 and 25;

25 Figure 27 shows a diagram reporting the result of a calibration standards set for a resistor load L4;

Figure 28 is a Smith Chart schematic representation showing a capacitance measurements comparison relating to the probe station and the ATE after the de-embedding phase of the present invention with the resistor load L4;

Figure 29 reports a diagram showing a corresponding correction factors array for the results of the Figures 27 and 28.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawing figures, generally shown at 1 an automatic test
5 equipment (ATE) according to an embodiment of the invention.

The inventive method is used to calibrate an Automatic Test Equipment (ATE) and to deembed the test boards at the wafer level. As previously noted, we will also refer hereinafter to the ATE with the brief appellation of "tester".

The inventive method comprises two main steps or phases. A first step is
10 the calibration of the automatic test equipment till the configuration plane.

Some OSL calibration standards are used to perform this method step.

A second step is a test board de-embedding in order to extend the calibration plane from the configuration board to the wafer pads.

A specific set of calibration standards provided on the device under test is
15 used to perform this second method step. These calibration standards have been characterized just for that purpose.

The de-embedding information that come out from the inventive method are used to adjust the measured RF signal levels.

The measurements have been performed on a RF transceiver. In order to
20 calibrate the tester till the Configuration-board plane, some OSL calibration standards have been provided, as explained in the following lines.

Then, the tester boards have been de-embedded, to extend the calibration plane from the configuration board to the wafer pads, using a set of said calibration standards on wafer specifically provided for this purpose. The de-embedding information
25 that come out from this method are used to adjust the mixer conversion gain and the output power level measurements of the RF tester.

The inventive method has been implemented on an Automatic Test Equipment (ATE) including a RF instrumentation, for instance an ATE known as Teradyne A585.

According to one embodiment of the invention the tester calibration and de-
5 embedding method improves the RF measurements accuracy on the automatic testing equipment for the IC wafers. The method steps are the following:

1. Tester automatic calibration
 - Up to the Internal Plane;
 - Automatically invoked by the system;
- 10 2. Calibration plane transfer
 - Up to the Configuration-Board Plane;
 - Using coaxial OSL standards;
3. Test Boards De-embedding
 - Up to the Wafer dice Plane;
 - 15 - Using specially made Calibration Standards on wafer.

We will now evaluate the tester calibration phase up to the configuration board plane and with reference to Figure 3.

Generally speaking, the invention allows to apply the S-parameters theory for de-embedding phase with the probecard needles.

20 If we consider that a two port passive network can be characterized by four complex parameters matrix, for example an S-parameters matrix, we may take in consideration the passive network shown in Figure 3.

If we assume that such a network is a passive and reciprocal transmission line of this kind:

25
$$S_{12} = S_{21}$$

then the above complex parameters become three.

According to this setting, it is possible to use a "Three-Term Error Adaptor" shown in Figure 4 in order to transfer the calibration plane from the section 1 of Figure 3 to section 2 of the same Figure 3.

In Figure 4 a passive and reciprocal network is shown, where:

$$\Gamma_{\text{meas}} = E_r / E_i = e_d + (e_r \bullet \Gamma_L) / (1 - e_s \bullet \Gamma_L)$$

and

$$e_d = S_{11}$$

$$e_s = S_{22}$$

$$e_r = S_{12} \bullet S_{21}$$

To calculate the unknown variables e_d , e_s and e_r we need three independent equations, that's three different known loads.

Usually the three loads used are Open circuit, Short circuit and a 50 Ohm load. For this reason this kind of calibration is called OSL (Open, Short, Load).

As reported above, the tester is able to perform an automatic calibration up to an internal plane. This operation can be done because the presence, inside the uwport (microwave port), of a "calibration module" and some switches that allow the system to connect internal Open, Short and Load and provide a reflection measurements.

Figure 5 is a schematic block diagram of a micro-wave port incorporated into a known tester of a standard calibration system for IC wafer testing and Figure 6 shows the waveform of a reflected microwave as compared to an incident wave.

In order to transfer the calibration plane from the Internal to the Configuration-board plane, as shown in Figure 2, the invention suggests to use three external OSP standard loads, which may be defined by the tester supplier.

In the case of the above mentioned Teradyne A585 tester, this transfer is executed by running an Image Progen function known as a command routine: "Transfer_External_Calibration", here is the algorithm list:


```

call Transfer_External_Calibration Frequencies: Incremental_Sweep

5   Start_Freq =      1.5GHz
    Stop_Freq =      2.5GHz
    Step =           10MHz
    Power_Level =     -25.0dBm
    Measure_Delta =    9
    Averages =         2
    Method:           One_Port
10   Pin =            RF_IN
    Std_file_open =    "open.slp"
    Std_file_short =   "short.slp"
    Std_file_load =    "load.slp"
    Int_Std_file_open = "internal_open.slp"
15   Int_Std_file_short = "internal_short.slp"
    Int_Std_file_load = "internal_load.slp":

```

Finally, after the transfer step, the calibration becomes active by running an Image Progen function known as a command routine: "Calibrate_S_Parameters_Internal",
 20 here is the algorithm list:

```

call Calibrate_S_Parameters_internal Frequencies: Incremental_Sweep

25   Start_Freq =      1.5GHz
    Stop_Freq =      2.5GHz
    Step =           10MHz
    Power_Level =     -25.0dBm
    Measure_Delta =    9
    Averages =         2
30   Method:           One_Port
    Pin =            RF_IN
    Int_Std_file_open = "internal_open.slp"
    Int_Std_file_short = "internal_short.slp"
    Int_Std_file_load = "internal_load.slp":

```

35 Now, we will consider the inventive method for designing the standards and the de-embedding procedure using such standards.

As a first approach, we have to consider the method used to generate the S-Parameters matrix of the whole block PIB plus Probecard. According to the present invention this method involves a technique defined as OSLR (Open-Short-Load-
 40 Reciprocal).

This technique is based on the use of three calibration standard loads on wafer specifically designed for the invention purposes. These calibration standards have

been designed directly using the same pad portions of the integrated device and the circuit layout has been optimized in order to have the best behavior of the loads with the minimum cost.

The Image function used and the theory, on which it is based, will be
5 described later.

To define the wafer calibration standards according to the present invention, a standard mask set of the DUT has been used, changing only the metal levels masks and the passivation mask.

In this modified mask the pads of the RF port to be tested have been
10 disconnected from the rest of the chip, and then connected to the calibration loads.

The whole frame includes twelve die positions, but only seven of them have been used for the calibration standards.

The following table represents the device under test frame on the wafer.

		L4
L3	L2	L1
C	S	O

15

Where:

"O" is the Open between the two pads, as shown in Figure 7;

"S" is the Short between the two pads, as shown in Figure 8;

"L1" represent the case in which a 50 Ohm resistor load is connected
20 between the two pads;

"L2" represent the case in which two 25 Ohm resistors loads are connected between each of the interested pads and their adjacent pad (Splitted configuration in Figure 9;

"L3" represent the case in which the same impedances of the device are
25 connected between the two pads of the interested port;

"L4" represent the case in which the same impedances' values of L3 are used, but in splitted configuration:

"C" is a Capacitance between the two pads, which is used to verify the correct execution of the whole calibration procedure.

5 All the other not interested pads of the device are shorted each other with a whole metal plane and with the device ground layer through all the device vias, as clearly shown in Figures 7 and 8.

This is a ground shield allowing a very good isolation from the integrated device circuits. Advantageously, this design method is independent from the integrated
10 device type.

Before using the above calibration standards in the de-embedding procedure, they have been characterized on a probe station, in a lab, with calibrated "Signal-Ground Cascade Probes" and in the frequency range from 1.5 to 2.5 GHz.

The characterization files are shown using a series of Smith Chart
15 representations that are shown in the pictures of the Figures form 10 to 16.

Let's now consider the de-embedding procedure.

The S-Parameter matrix of Figure 3, that characterizes the whole block PIB plus Probecard, is generated by running an Image Progen function known as a command routine: "Create_Deembed_File_OSLR" in the above mentioned ATE Terayne A585, here
20 is the algorithm list:

```
call Create_Deembed_File_OSLR Frequencies: Incremental_Sweep  
  
25 Start_Freq = 1.5GHz  
Stop_Freq = 2.5GHz  
Step = 10MHz  
Power_Level = -25.0dBm  
Measure_Delta = 9  
Averages = 2  
30 Method: One_Port  
Pin = RF_IN  
Std_file_open = "op.slp"  
Std_file_short = "sh.slp"  
Std_file_load = "ll.slp"  
35 Deembed_File = deemb_on_wafer.s2b
```

The inputs to this function are the three s1p files that characterize the wafer standard loads (Open, Short and Load). After the three measurement steps of these loads a s2p file (the de-embedding file) is created.

This s2p file can be accepted as input by an Image Progen function known
5 as a command routine: “Measure_S_Parameters”, which is used to measure the S11 parameter at one port, here is the corresponding algorithm list:

```
call Measure_S_Parameter Frequencies: Incremental_Sweep  
10 Start_Freq = 1.5GHz  
Stop_Freq= 2.5GHz  
Step = 10MHz  
Power_Level = -25.0dBm  
Measure_Delta = 9  
15 Averages = 2  
Method: One_Port  
Pin = RF_IN  
Deembed_File = deemb_on_wafer.s2p  
One_Port_File = Capacitance_gamma.s1p  
20
```

In this way the inventive method allows to verify the test-boards de-embedding, see for instance the example of Figure 17, measuring the fourth calibration load the corresponding capacitance has been designed on the wafer.

The comparison between the measurements after the de-embedding and the
25 characterization, done on the probe station, is shown in the following lines.

The last step of the whole work is to apply all the previous procedure to the DUT normal test.

When a RF signal from the device is measured or sourced to the port pads, normally some power losses due to the mismatching between tester equipment and device
30 occur. These losses are related to power reflection at that port and then become known once the S11 parameter of the device, at that section, is measured. Using the Image Progen function “Measure_S-Parameters”, it is possible to measure the S11 parameter, and then the scalar correction factor is evaluated by a function “Level_Adjust”.

Here are the corresponding algorithms:
35

```

call Measure_S_Parameter Frequencies: Incremental_Sweep

5   Start_Freq =      1.5GHz
    Stop_Freq =      2.5GHz
    Step =           10MHz
    Power_Level =     -25.0dBm
    Measure_Delta =    9
    Averages=         2
10   Method:         One_Port
    Pin =             RF_IN
    Deembed_File =     deemb_on_wafer.s2p
    One_Port_File =    dut_gamma.slp
    Es_File =          es_file.slp

15   call Level_Adjust

    Correction:        Source
    Source_Match:      File
20   SM_File =        es_file.slp
    Technique:         Transducer_Gain
    Dut_input_gamma =  "dut_gamma.slp"
    Deembed_File =     deemb_on_wafer.s2p
    Num_Freqs =        101
25   Correction_Array = correction_factors_array

```

The correction factors' values are shown, among the results, hereinafter.

The following table reports a verification capacitance measure comparison between the probe-station and the tester, and the correction factor array, in the frequency range from 1.5 to 2.5 GHz.

These results are shown with reference to the interesting RF port and the de-embedding file.

Moreover, the results are shown in the Figures for each of the four calibration standards sets, which differ each other for the resistor load (L1, L2, L3 and L4). The table below summarizes the comparison between the final correction factors, at one frequency, found using our procedure and the usual correlation with the bench measurements.

L1	L2	L3	L4	BENCH
2.4 dB	2.4 dB	2.9 dB	3.0 dB	3.2 dB

The Figure 18 shows a diagram reporting the result of a calibration standards set for the resistor load L1 while the Figure 19 is a Smith Chart schematic representation showing a capacitance measurements comparison relating to the probe station and the ATE after the de-embedding phase of the present invention with the load
5 standard L1.

Figure 20 reports a diagram showing a correction factors array.

The other Figures show the same results for the other loads: L2, L3 and L4 respectively.

The main important result of the inventive method is that the de-embedding
10 phase of the test board block, PIB plus Probecard, is possible using wafer calibration standards, specifically designed for this purpose.

The design methodology for the standards is well working and it is applicable to every kind of device and technology.

The achievements are confirmed by two results:

- 15
1. The verification using the capacitance (Figures 19, 22, 25, 28) shows a very good approximation between the probe-station and the ATE measurements.
 2. The final correction factors calculated after de-embedding, using the disclosed procedure, confirm the values estimated by the usual
20 correlation between the measurements on bench and on the ATE.

In particular, the calibration sets with the loads L3 and L4 give the best performances.

Furthermore, no relevant differences between the results obtained using the calibration set, with splitted and unsplitted configuration, have been observed.

25 Therefore, a calibration standard set, with a single load between the two pads can be used also for differential ports. It must be noted that between the L1/L2 and L3/L4 load sets it has been that the best approximation is achieved by using the L3 or L4 set. This means that, generally, it is recommended to design the calibration standard loads

as near as possible to the device impedance at that port, in order to minimize the unwanted mismatching reflections and get the best measure accuracy.

Another important achievement is that the disclosed design methodology allows obtaining calibration standards on wafer, using the same diffusion process as the device under testing. In this way we can get two main advantages:

1. The modification of only a minimized set of masks is required
2. Low cost technique.

Moreover the use of calibration standards on wafer reduces drastically the cycle-time for the correction factors evaluation to :

10 $T < 1 \text{ day}$

and so, the inventive method is very useful in the production environment too.

The method according to the present invention obtain many advantages with respect to the prior art solutions and namely:

- 15 - it allows obtaining absolute values for the RF measurements on wafer using an ATE;
- it allows obtaining the ATE measurements independent from the bench measurements;
- it avoids the operation of correlation with the bench;
- 20 - low cost calibration standards are obtained on the wafer since the same diffusion process used to manufacture the device under test is implemented for the standards too; just a minimum set of marks are modified for this purpose.